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Major coastal impact induced by a 1000-year storm event

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Extreme storms and storm surges may induce major changes along sandy barrier coastlines, potentially causing substantial environmental and economic damage. We show that the most destructive storm (the 1634 AD storm) documented for the northern Wadden Sea within the last thousand years both caused permanent barrier breaching and initiated accumulation of up to several metres of marine sand. An aggradational storm shoal and a prograding shoreface sand unit having thicknesses of up to 8 m and 5 m respectively were deposited as a result of the storm and during the subsequent 30 to 40 years long healing phase, on the eroded shoreface. Our results demonstrate that millennial-scale storms can induce large-scale and long-term changes on barrier coastlines and shorefaces, and that coastal changes assumed to take place over centuries or even millennia may occur in association with and be triggered by a single extreme storm event.

Coastal changes related to extreme storms are predominantly caused by wave and current driven processes in interaction with the strength and duration of the storm surge¹ and by post-storm recovery^{2–4}. Several studies have investigated the effects of storms on coastal geomorphology^{5–13}, establishing that storms exert a significant degree of control on short-term coastal evolution^{4,14,15}. The scale of storm-related coastal changes has been documented mostly through shore profile measurements, comparison of topographic and bathymetric data, photogrammetry and more recently, using ground penetrating radar or high density LiDAR data^{12,16–19}. Despite numerous investigations concerning the effects of storms on sandy barrier coastlines, no studies have identified or quantitatively documented coastline and shoreface changes caused by a single historic thousand-year storm event. Such information is essential for evaluating the long-term effects of episodic erosion and deposition caused by extreme storms in shallow coastal environments, and for improving coastal management. Documenting the effects of major storm events is also critical to the interpretation of ancient sedimentary deposits.

Here we describe the detailed chronology of sedimentation related to a single extreme storm event that impacted the Danish and German Wadden Sea coast (Fig. 1a) on the night between 11 and 12 October 1634 AD²⁰. This event is considered to be one of the largest and most devastating storms ever recorded along the Wadden Sea coast, and caused thousands of deaths along the affected coastline²⁰ together with large scale changes of the coastal landscape^{21,22}. The Wadden Sea is a sub- and intertidal zone of the North Sea, bordering the northwestern part of continental Europe. It consists of a chain of 23 barrier islands and extends c. 500 km north from Den Helder, Netherlands to Blåvandshuk, Denmark. Tides along the Danish coastline of the Wadden Sea are semidiurnal with a mean tidal range of 1.5 to 1.8 m. Wind set-up occasionally contributes to an astronomical tidal range with more than 2 m. The highest recorded sea-level in Danish areas of the Wadden Sea is about 6.1 m, a mark reached in Ribe Cathedral 20 km north of Rømø during the 1634 AD storm event. This level is a metre higher than the second highest sea-level ever recorded. The disparity among recorded sea-level heights and other historical evidence indicate that the 1634 AD storm surge was unique and by far the highest in the area since approximately 1250 AD in Ribe. According to extreme sea-level statistics from the Danish Coastal Authorities the recorded sea-level during the 1634 AD storm will have a return period of 5000 to 6000 years (see Methods and Fig. 3). However, to take into account any uncertainties regarding the recorded sea-level during the storm together with the inherent uncertainties related to extrapolation of storm surge statistics we conservatively classify the storm as a thousand-year event.

Results

Ten sites along the Danish coastline of the Wadden Sea were cored and sampled (Fig. 1a) for this study. The sediment was analysed for features recording its depositional environment (Supplementary Information), and then sampled for dating using optically stimulated luminescence (OSL; 49 samples). The OSL data were used to

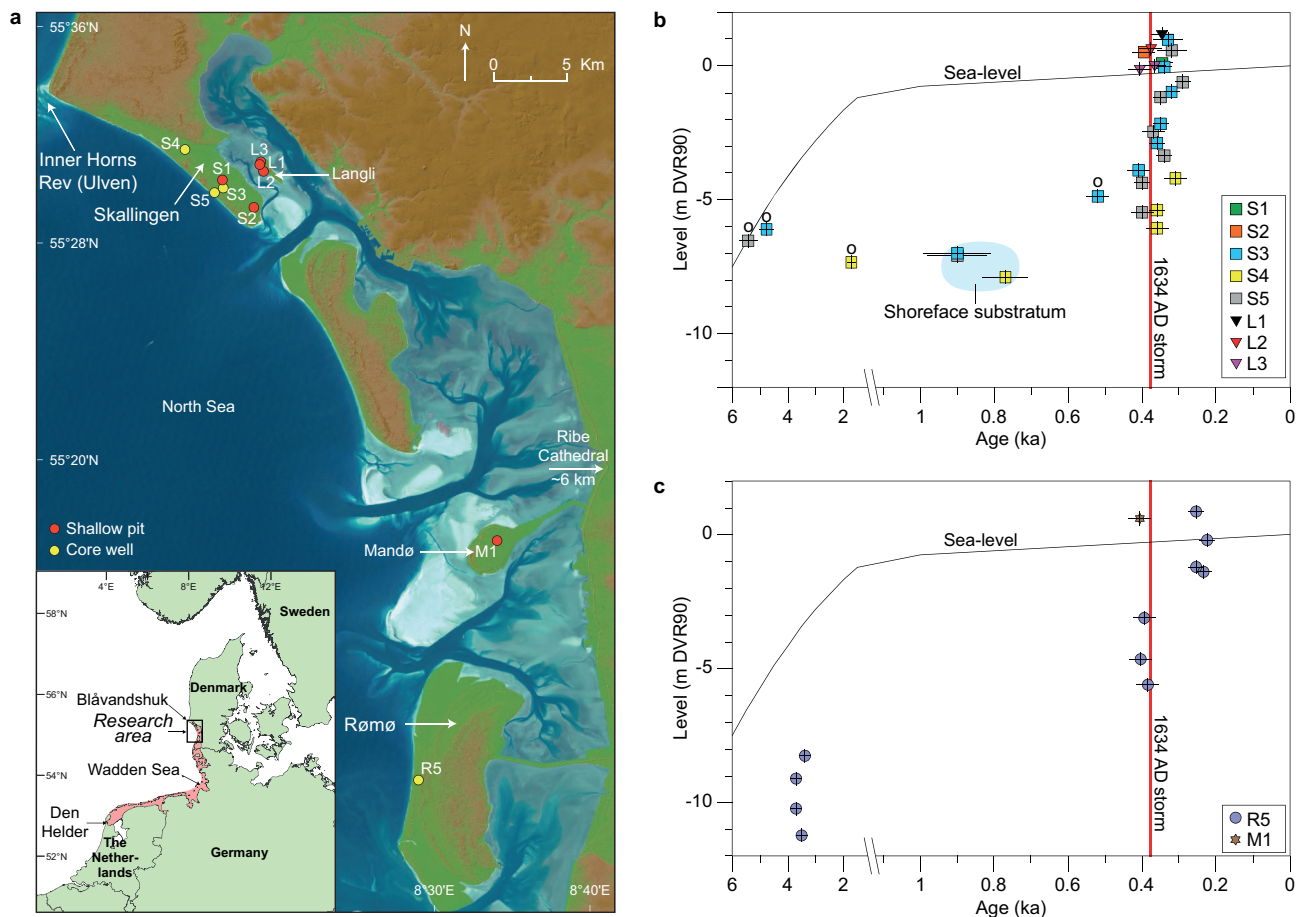


Figure 1 | Sample locations and OSL ages plotted in sediment sea-level diagrams. (a) The location of the Wadden Sea coast (inset; light red area) shown with 10 sample localities from which sediment was collected (red and yellow circles). (b) OSL ages (ka relative to 2010, 1σ uncertainty) from cores S1–S5 and L1–L3; ‘o’ indicates overestimation of the OSL age. The red solid line marks the time of the 1634 AD storm and the black solid line represents the relative mean sea-level curve for the study area after ref. 47. (c) OSL ages (ka relative to 2010, 1σ uncertainty) from cores M1 and R5. The vertical uncertainty for OSL samples from core wells is ± 0.25 m, and ~ 0 m for OSL samples from excavation pits (Supplementary Information).

construct a high-resolution chronology of the sediment cores extending back approximately 3600 years (Methods and Supplementary Tables S1 and S3). Core sediment from the barrier peninsula of Skallingen (Fig. 1a, locations S3–S5) was mainly composed of (1) basal shoreface and sub-marine shoal sand, (2) washover fan sand and (3) an uppermost unit of aeolian sand (Supplementary Information and Supplementary Figs. S1 and S2). At the barrier island of Rømø, about 40 km south of Skallingen (Fig. 1a, location R5), core sediment consisted of shoreface sand overlain by backshore sand.

A total of 25 OSL ages (data from this study and from ref. 23) are presented (Fig. 1b). These include three basal shoreface sand ages and 22 ages for the aggradational shoal sand from Skallingen (Fig. 1a, locations S1–S5). The shoreface sands gave an average OSL age of 0.86 ± 0.08 ka and thus provide constraint on the timing of substratum deposition. The 22 aggradational shoal sand samples spanned about 8 m of vertical thickness, and gave OSL ages ranging from 5.43 ± 0.32 to 0.29 ± 0.02 ka. Eighteen aggradational shoal sand samples from the upper ~ 7 m of the sections cored ranged from 0.41 ± 0.03 to 0.29 ± 0.02 ka. The OSL ages from the upper 7 m of the aggradational shoal sand all coincide, or nearly coincide with the 1634 AD storm event. OSL samples from cores S3, S4 and S5 show a tendency for upward decreasing ages suggesting that these sediments were deposited progressively during a healing phase that may have lasted three to four decades after the storm. The four OSL ages (5.43 ± 0.32 to 0.52 ± 0.03 ka) from the lowermost part of the aggradational shoal sand deposits appear to be substantially older

than the 1634 AD event, probably due to incomplete bleaching of the quartz grains (see Methods and Supplementary Information). These initial deposits accumulated at relatively large water depths, in high turbidity conditions with large amounts of suspended sediment, all serving to reduce ambient light levels. Under these conditions, the probability of incomplete bleaching of basal samples is high, and the OSL ages of these samples are likely to significantly overestimate depositional age^{24,25}. Samples showing evidence of incomplete bleaching were recovered from three different cores at approximately the same elevation (relative to mean sea-level), supporting the interpretation that sediments having apparently divergent OSL ages were actually deposited by the same event. The total vertical range spanned by the 22 samples of aggradational shoal sand is between 7 and 8 m. The uppermost level of the aggradational shoal sands range from about 0.5 to 1 m above modern mean sea-level in Denmark. This would correspond to a height of approximately 0.75 to 1.25 m above mean sea-level in 1634 AD (Fig. 1b). Given a tidal amplitude comparable to that observed at present²⁶, the aggradational shoal would have reached into the supratidal zone. The results signify that the 1634 AD storm induced shoreface erosion followed by near-instantaneous deposition of between 0.5 and 1 metre of sediment. In the healing phase of the 1634 AD storm rapid progressive deposition continued in three to four decades resulting in the formation of a 7 to 8 metre thick aggradational shoal.

Four OSL ages²³ from the west coast of Langli fall within the time frame of the 1634 AD storm (Fig. 1b and Supplementary Table S2).



Langli is an island presently protected by lee effects of the Skallingen peninsula (Fig. 1a). The coeval OSL ages suggest that sediment erosion and deposition related to the 1634 AD storm were especially intense along the seaward side of Langli, and that Skallingen had not yet formed a protective barrier to the west.

Historical maps from 1612 AD and 1650 AD (before and after the storm; Fig. 2a and b) confirm that major coastal changes occurred during this period, consistent with our interpretation of the OSL chronology. The 1612 AD map (Fig. 2a) shows Langli as a spit, and open water at the present day location of Skallingen (compare Fig. 2a and d). The 1650 AD map (Fig. 2b) shows the barrier peninsula of Skallingen as a high-lying sand shoal and Langli as an island. These maps and the OSL ages from Langli suggest that erosion associated with the storm breached the Langli spit. The map of the study area from 1695 AD shows Langli and Skallingen in a configuration similar to that observed today (Fig. 2c and d). The breach of the Langli spit and the formation of a supratidal aggradational shoal resulted in a significantly changed coastline extending 3.5 to 4 km seaward relative to the pre-1634 coastline (Fig. 2a and b).

The results presented above pertain to the coastline along northerly areas of the Danish Wadden Sea but evidence of the storm appears in other regions as well. We detected effects of the 1634 AD storm on two barrier islands, Mandø and Rømø, located c. 30 and 40 km south of Skallingen, respectively (Fig. 1a). The eleven OSL ages²⁷ (Supplementary Table S3) of shoreface sand in core R5 from Rømø (Fig. 1a) indicate three rapid depositional phases occurring at approximately 3.6 ± 0.2 , 0.39 ± 0.03 and 0.24 ± 0.02 ka and suggests substantial erosion and deposition associated with three storm surges (Fig. 1c). Each of the three depositional phases corresponds to a shoreface succession which is bound downward and upward by sharp boundaries. The upper succession corresponds with a storm in 1770 AD²⁰, whereas the 5 m thick middle succession is coeval with the 1634 AD storm. From the relative positioning of the three OSL ages and the timing of the second phase, we estimate that at least 2.5 m of deposition occurred during and in not more than two decades after the 1634 AD storm. The OSL chronology for the R5 core thus suggests punctuated episodes of shoreface sedimentation in which three sedimentary successions accumulated within very short time intervals. We interpret the sedimentary record from the core as reflecting repeated and substantial reworking of the shoreface by three major storms followed by rapid shoreface healing (see Supplementary Information).

Discussion

The OSL chronologies of coastal sediments presented here indicate that extreme storms can redistribute substantial amounts of sediment in the coastal zone and induce rapid (near-instantaneous to decadal-scale), large-scale changes in the coastline. The widespread large-scale coastal changes which occurred along the whole northern Wadden Sea coastline during and after the 1634 AD storm, highlight the potential impact of millennia-scale storms and storm surges. Our results suggest that a single extreme storm can influence not only short-term (<10 years) coastal changes⁴ but also trigger long-term (>100 years) coastal changes. This study offers the first documentation of how a major storm event can lead to the formation of supratidal marine shoals, which may evolve into barrier islands, spits or peninsulas in certain coastal settings.

Two main processes may have been responsible for the observed response of the 1634 AD storm at the Skallingen coast: southward directed longshore transport and seaward and landward directed cross-shore transport. South-westerly winds would have favoured waves entering the coast in a shore normal direction resulting in offshore directed bottom return flow and sediment transport. This process has been documented in several studies^{28–31}. At Skallingen both offshore and onshore directed sediment fluxes during storms has been reported³². Recent research (Frøerger et al., *in prep*)

conducted on the pre 1634-coastline has dated the marine base, presently underlying aeolian sediments, to have been deposited 5.5 to 1.4 ka ago. This age is comparable to the age of the lower part of the aggradational storm shoal (the overestimated ages in Fig. 1b). This concurrence in the age of the sediment composing the pre-storm exposed coastline and the sediment in the lower most part of the aggradational shoal indicate that sediment eroded at the coastline was entrained in an offshore directed current and deposited as the base of the aggradational storm shoal. Seaward directed bottom return flow and transport would primarily have taken place until the breach of the Langli spit whereafter washover at the spit would have generated a net onshore-directed flow.

In addition to the cross shore sediment transport, a north-westerly wind direction would have resulted in waves of oblique incidence, giving strong longshore currents and southward directed sediment transport. Presently, the southward directed longshore transport of sand is estimated to average $640,000 \text{ m}^3 \text{ yr}^{-1}$ and it is an important component in controlling the morphological development of the modern Skallingen³³. The approximately 19 km² large Inner Horns Rev shoal (Ulven) located in continuation of the northern part of Skallingen constitutes a major sediment source ($58 \times 10^6 \text{ m}^3$ of sand)^{34,35}. According to ref. 35 the young age of Ulven (only about 300 years) could owe to the fact that the area of Ulven is a transient sediment trap which periodically is eroded and the sediment dispersed southward entrained in the dominant longshore current. A strong longshore sediment flux initiated by the 1634 AD storm could have caused a rapid progradation of a paleo Ulven towards the location of the present Skallingen. Assuming a longshore transport rate comparable to the present, the foundation of Skallingen could have been deposited during two or three decades which is within the uncertainty range of the OSL ages.

Multiple storms impacted the Danish Wadden Sea area in the first half of the 17th century. At least six larger and possibly a number of smaller storm surges impacted the coastline of the northern Wadden Sea throughout the 1630s–40s²⁰. Multiple storms in quick succession have been recognised to have a large impact on coastal morphology³⁰. However, it is notable that age inversions in the chronology (Fig. 1b) are only identified in the lowermost part of the aggradational storm shoal succession and furthermore, that the aggradational shoal sediment is very homogeneous and without distinct multiple erosional surfaces. These observations suggest that the deposition of the lower part (0.5–1 m) of the aggradational shoal formed almost instantaneous during the waning phase of the 1634 AD storm and that the subsequent deposition of the upper 7 m of the shoal succession occurred progressively and rapidly with any succeeding storms having less impact on the sedimentation patterns and morphology relative to the 1634 AD storm event.

Although Skallingen and Rømø are relatively closely situated (c. 40 km), important differences in morphology and sediment supply explain why aggradational shoal sand accumulated in the northern research area and prograding shoreface sand in the southern. The main distinction in depositional pattern between the two sites relates to sediment availability after the 1634 AD storm. Immediately after the storm both localities received large amounts of sediment healing the shoreface. At Skallingen this supply decreased after the sediment source of a paleo Ulven was depleted. Most likely the depositional locus shifted back to Inner Horns Rev, forming the present Ulven and resulting in a progressive retrogradation of Skallingen as seen today. From old maps it can be documented that the exposed west coast of Skallingen has been receding since at least 1804^{36,37}. At Rømø sediment accumulation sustained after the initial shoreface healing phase due to the islands location at the base of a large embayment which was and still is the depocenter of the coastline and led to the continued long-term aggradational and progradational development of the barrier island²⁷ (Fig. 1a). The differences in long-term sediment supply may also explain why the third sedimentation period

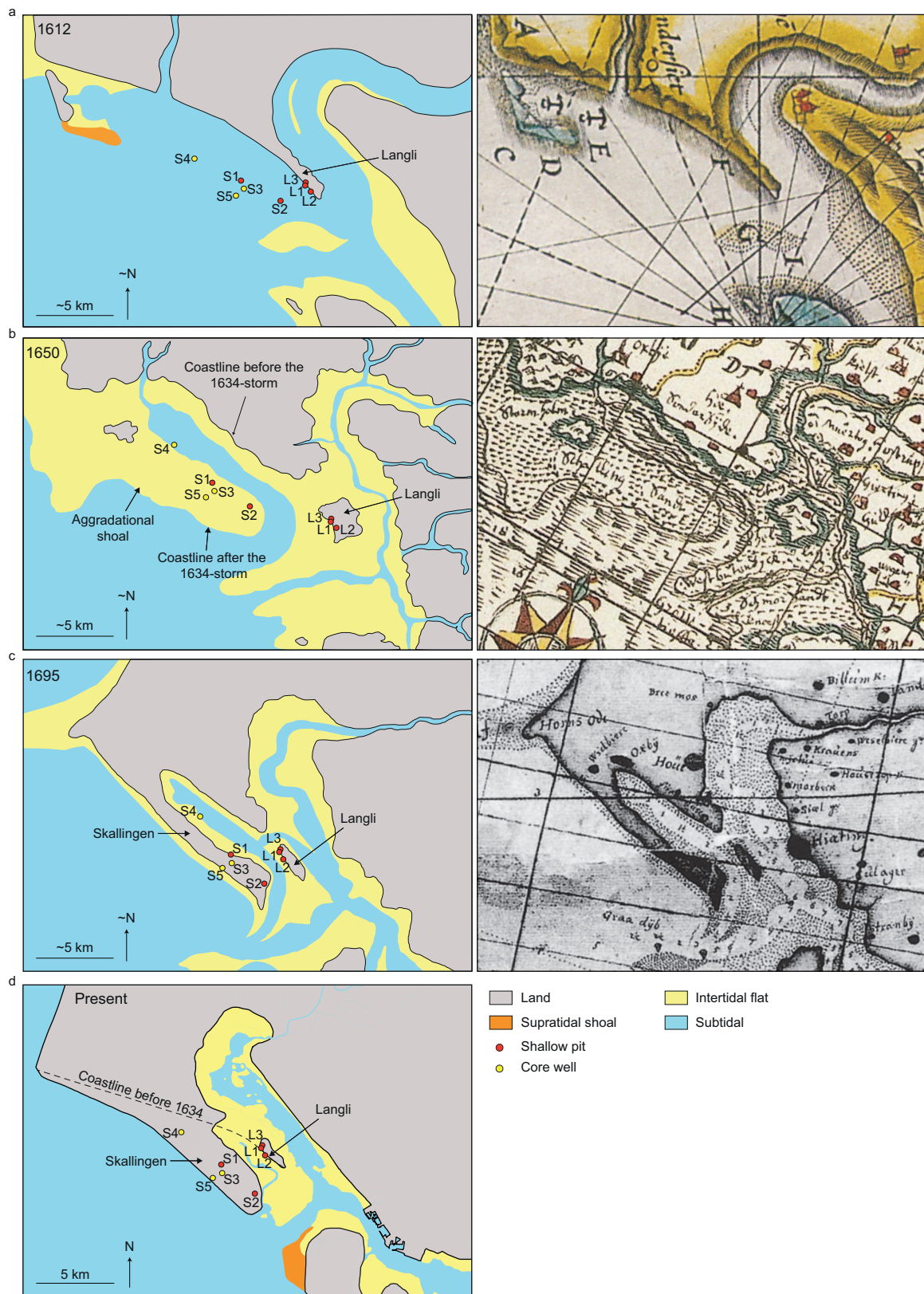


Figure 2 | Reconstruction of the coastline before and after the 1634 AD storm. (a) Interpretation of Willem Janszoon Blaeu's map anno 1612 AD⁴⁸. Open water condition existed at the Skallingen localities sampled by this study and Langli formed a barrier spit. (b) Interpretation of Johannes Mejer's map anno 1650 AD⁴⁹. Sample localities coincide with an aggradational sand shoal referred to as Schallingsand, and Langli is represented as an island. The 1650 map does not differentiate between intertidal and supratidal flats but the storm shoal occurs in the supratidal zone according to sediment sea-level diagrams (Fig. 1b). With the formation of the storm shoal the coastline was displaced seaward 3.4 to 4 km relative to the 1612 AD coastline. (c) Interpretation of Jens Sørensen's map anno 1695 AD⁵⁰. Approximately 60 years after the storm, Skallingen is represented as a supratidal sand shoal. (d) The present coastal configuration. Note that maps shown in panels a through c have not been geo-referenced. The locations of core sites are therefore only approximate.

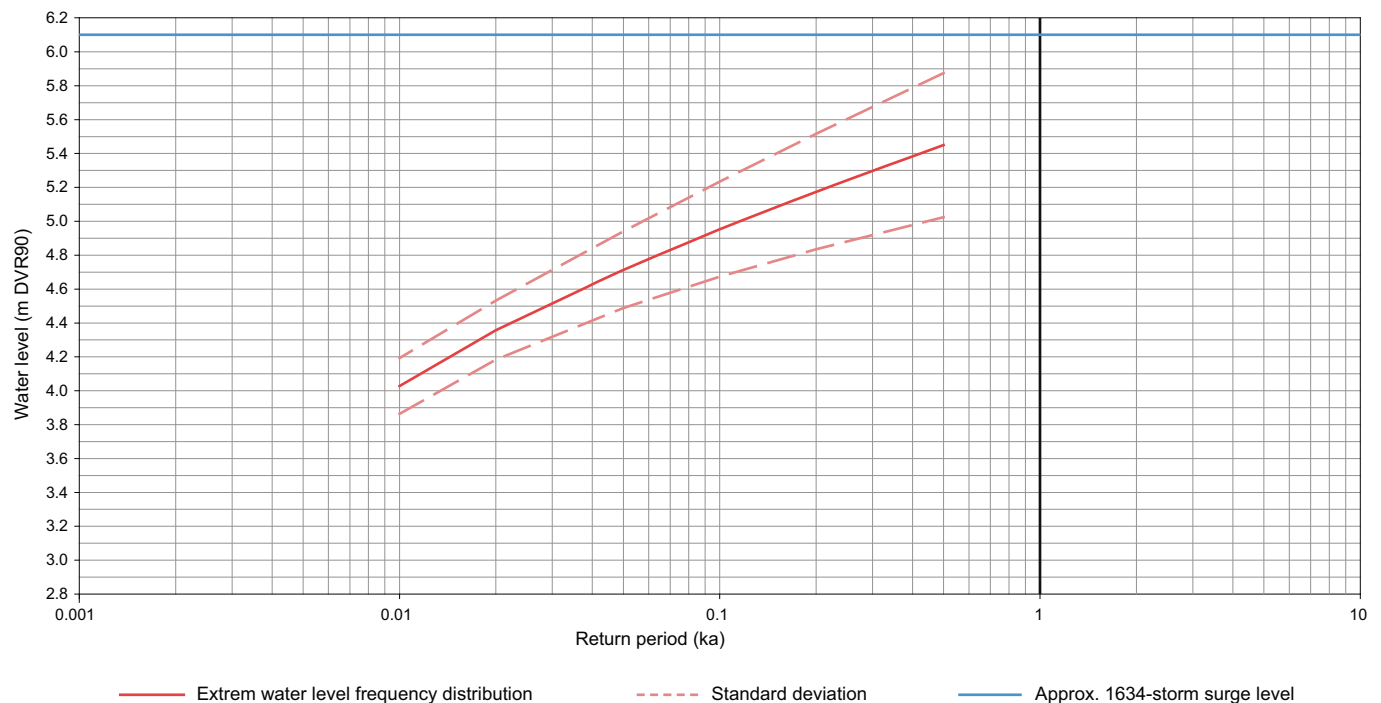


Figure 3 | Extreme water level frequency distribution for the water level gauge in Ribe. The blue line marks the approximately 1634 AD storm surge level at 6.1 m DVR90. A comparable water level is statistically expected to occur with a frequency less than once per thousand years⁴³.

(0.24 ± 0.02 kyr ago) in core R5 from Rømø has not been observed in the sediment archive of Skallingen. This difference most likely results from the variation in preservation potential at the two sites. The regressive nature of Rømø favours burial and preservation of storm scarps whereas the opposite applies for the transgressive Skallingen.

Coastline erosion and destruction of salt marshes is known consequences of the 1634 AD storm^{21,22}. However, to the knowledge of the authors, no studies on the 1634-storm have reported deposition of a several metre thick aggradational shoal as identified in this study. The reason for this can originate in differences in geological and morphological inheritance and sediment supply of the research area of Skallingen compared to other areas affected by the storm. However, it is also likely that our application of high-resolution down-core OSL dating, a method rarely used in other studies, explains the discrepancy between the identified storm deposition patterns observed in this study compared to other studies. Comparable erosional/depositional patterns as observed at Rømø have been identified in a number of studies in both modern to sub-modern deposits as well as in ancient deposits^{18,19,24,38}.

The topographic, stratigraphic and sedimentological response of a barrier island chain to a severe thousand-year storm event is pertinent to interpretations of other modern and ancient sedimentary deposits. Storm deposits, especially those forming from extreme events, are known to be preferentially preserved compared to sediments forming under quiescent or fair weather marine conditions²⁴. This study strongly supports that claim. Previously reported storm sand deposits are no more than c. 2 m thick²⁴. This study shows that millennial-scale storms can result and trigger deposition of several metres of storm sands at the shoreface. Given their thickness, these deposits will have high preservation potential in the geological record.

Climatological models of tropical and extratropical storms indicate that global climate change and associated higher sea surface temperatures will cause an increase in the intensity of the most severe storm events^{39,40}. Large-scale coastal changes may consequently occur on shorter time scales, above and beyond coastal changes⁴¹ promoted by general global sea-level rise⁴². Together, these two factors highlight future challenges and the need for adaptive coastal management policies in the coming centuries.

Our study also demonstrates that OSL dating can be used to quantify the storm-induced coastal impact in ancient deposits. Improved interpretation of storm related coastal changes in the geological record can provide important constraints on models for coastal evolution, and thereby contribute to the understanding and prediction of the impact of future extreme storms. In the coming centuries, sandy barrier coastlines throughout the world may experience changes similar in magnitude to those caused by the 1634 AD Wadden Sea storm. Fully understanding the potential impacts of major storms is critical in evaluating coastal hazards associated with these events.

Methods

Evaluation of the relative strength of the storm surge in 1634 was done by comparison with storm surge statistics published in a report by the Danish Coastal Authorities⁴³. According to that report storm surge levels reaching 5.65 m above mean sea-level occurs about once every 1000 year in Ribe⁴³. During the 1634 AD storm 1634 the recorded sea-level reached approximately 6.10 m above mean sea-level in Ribe. This level statistically occurs only about once every 5000 to 6000 years. To take into consideration that the recorded sea-level during the 1634 AD storm may have been overestimated and the statistically errors which occurs when extending the extreme water level frequency distribution in Fig. 3 beyond the 500 year return period, we conservatively consider the recorded water level during the 1634 AD storm to have a return period of at least 1000 years.

Samples subjected to OSL dating were collected from 10 core wells and excavation pits along the Danish areas of the Wadden Sea coast (Fig. 1a). Both northern and southern extremities of the Danish Wadden Sea coast were included as sample localities to ensure that the material dated was regionally distributed. Sediment cores were collected using a powered hollow auger corer with opaque core-tube inserts. Sediment was also collected from manually excavated pits. At these localities, sample tubes were horizontally inserted into fresh vertical surfaces of the excavation pit. Care was taken to ensure that only marine sediment was collected. The position and elevation of all core wells and excavation pits were recorded using a Trimble R8 differential GPS with a vertical accuracy of ± 0.02 m. All vertical points of reference are given relative to the 1990 Danish Vertical Reference system (DVR90), which approximately corresponds to modern mean sea-level. Luminescence measurements of quartz sand grains were performed using automated Risø TL/OSL readers^{44,45} with equivalent doses determined using a single aliquot regenerative (SAR) dose protocol⁴⁶. Radionuclide concentrations were measured using high-resolution gamma spectrometry and converted to dose rates. Dates given in the text are in calendar years and OSL ages are relative to the year 2010 AD.

Interpretations of depositional environments are based on analysis of clast size, sedimentary structures, texture, degree of bioturbation and trace fossil content. Seven



depositional units were identified from cores S3, S4, S5 and R5. This paper specifically describes the shoreface sand and aggradational shoal sand units. Detailed descriptions of OSL methods, stratigraphic information and interpretations of depositional environments are given in the Supplementary Information.

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Author contributions

All authors have taken part in conceiving and executing this research. M.P., T.J.A. and L.H.N. conducted the fieldwork. All authors have contributed to data analysis and interpretation. M.F. wrote the paper with contributions from all authors.

Additional information

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